Available online at www.sciencedirect.com
SCIENCE DIRECT®

Remote Sensing of Environment 86 (2003) 566–577

Remote Sensing of Environment

www.elsevier.com/locate/rse

# Consideration of the errors inherent in mapping historical glacier positions in Austria from the ground and space (1893–2001)

Dorothy K. Hall[a,*], Klaus J. Bayr[b], Wolfgang Schöner[c], Robert A. Bindschadler[d], Janet Y.L. Chien[e]

[a] Code 974, NASA/Goddard Space Flight Center, Greenbelt, MD 20771, USA
[b] Department of Geography, Keene State College, Keene, NH 03435-2001, USA
[c] Klimaabteilung, Zentralanstalt für Meteorologie und Geodynamik—ZAMG (Central Institute of Meteorology and Geodynamics—ZAMG), Hohe Warte 38, Vienna A-1190, Austria
[d] Code 971, NASA/Goddard Space Flight Center, Greenbelt, MD 20771, USA
[e] General Sciences Corporation, Laurel, MD 20707, USA

Received 31 December 2002; received in revised form 28 April 2003; accepted 3 May 2003

**Abstract**

The historical record of in situ measurements of the terminus positions of the Pasterze and Kleines Fleißkees glaciers in the eastern Alps of Austria is used to assess uncertainties in the measurement of decadal scale changes using satellite data. Topographic maps beginning in 1893, and satellite data from 1976 to 2001, were studied in concert with ground measurements to measure glacier changes. Ground measurements show that the tongue of the Pasterze Glacier receded ~ 1150 m from 1893 to 2001, while satellite-derived measurements, using August 2001 Landsat Enhanced Thematic Mapper Plus (ETM+) data registered to an 1893 topographic map, show a recession of 1300–1800 m, with an unknown error. The measurement accuracy depends on the registration technique and the pixel resolution of the sensor when two satellite images are used. When using topographic maps, an additional source of error is the accuracy of the glacier position shown on the map. Between 1976 and 2001, Landsat-derived measurements show a recession of the terminus of the Pasterze Glacier of 479 ± 136 m (at an average rate of 19.1 m $a^{-1}$) while measurements from the ground showed a recession of 428 m (at an average rate of 17.1 m $a^{-1}$). Four-meter resolution Ikonos satellite images from 2000 and 2001 reveal a shrinkage of 22,096 ± 46 $m^2$ in the Pasterze tongue. The nearby Kleines Fleißkees glacier lost 30% of its area between 1984 and 2001, and the area of exposed ice increased by 0.44 ± 0.0023 $km^2$, according to Landsat satellite measurements. As more recent satellite images are utilized, especially data that are geocoded, the uncertainty associated with measuring glacier changes has decreased. It is not possible to assess the uncertainty when an old topographic map and a satellite image are coregistered.


*Keywords:* Mapping; Glacier; Austria

## 1. Introduction

Glaciers throughout the Northern Hemisphere have been losing mass. Hölzle, Dischl, and Frauenfelder (2000) showed net mass balance decreases in 32 glaciers in the Northern Hemisphere in 10 different mountain ranges between 1980 and 1997, with the mean thickness change about − 0.3 m $a^{-1}$. Globally, small glaciers have generally been receding on all continents with the exception of Antarctica, where the mass balance of the ice sheet is poorly known (Dyurgerov, 2002). While much has been written about glacier changes from space, few studies show quantitative changes compared to ground measurements over a decadal time frame, precluding the establishment of measurement errors.

In this paper, we discuss changes of two glaciers in the eastern Alps of Austria: the Pasterze and the Kleines Fleißkees. More than 100 years of in situ measurements have been made on these glaciers. The excellent record of in situ measurements has permitted us to assess the accuracy of satellite-derived measurements of the Pasterze and Kleines Fleißkees glaciers, and historical ice front position changes of the Pasterze, using ground observations, Landsat and Ikonos satellite imagery, and topographic maps.

* Corresponding author.
*E-mail address:* Dorothy.K.Hall@nasa.gov (D.K. Hall).

0034-4257/03/$ - see front matter © 2003 Elsevier Inc. All rights reserved.
doi:10.1016/S0034-4257(03)00134-2

## 2. Background

Glaciers of the European Alps are retreating in response to regional climatic change. There has been a general increase in average (May through September) temperature and a decrease in the number of days with snowfall between May and September since 1886 (Bayr, Hall, & Kovalick, 1994; Böhm, 1986; Schöner, Auer, & Böhm, 2000). Since about 1850, the total areal extent of glacierized areas in the European Alps has decreased by about 35%, while the volume of ice has decreased by about 50% (Haeberli, Cihlar, & Barry, 2000; Haeberli & Hölzle, 1995). The meltwater from the glaciers in the Alps is very important to the generation of power and, along with seasonal snow cover, the glaciers are the primary sources for such major rivers as the Rhine, Rhone, Po, and Inn.

Glacier behavior in the Austrian Alps before 1850 is not well known; however, there are several reports about maximum stages around 1600–1650, 1770–1780, 1815–1820, and 1850–1860. Knowledge is especially poor during periods when the glaciers were in retreat (e.g., see Nesje & Dahl, 2000). Glaciers receded until about 1910, with the most important maximum of the 20th century occurring around 1920; there was a second minor maximum around 1980. Most of the glaciers stopped advancing in the mid-1980s due to warm summers and reduced snowfall. In 1988, about 80% of the Austrian glaciers were in recession (Rott, 1993).

There are 925 glaciers with a total area of 542 $km^2$ in the Austrian Alps. Five are larger than 10 $km^2$, but the majority are smaller than 1 $km^2$ as determined from aerial photographs taken in 1969. The Pasterze Glacier is the largest in Austria with an area of 19.8 $km^2$ in 1969 (Rott, 1993; Williams & Ferrigno, 1993).

The Pasterze Glacier (47°6′N, 12°42′E) flows from the Johannisberg (3463 m) and is located in the Hohe Tauern, which is a part of the Alps that extends east of the area around the Rhine River (Fig. 1). The highest peak in Austria, the Grossglockner (3798 m), is located to the southwest of the Pasterze and its hanging glaciers contribute some ice and morainal material to the Pasterze. Annual measurements of the Pasterze tongue were started in 1880 and continue to the present, providing an excellent record of glacier recession (Österreichischer Alpenverein, 1999/2001; Wakonigg, 1991). Between 1979 and 1989, the mean equilibrium line altitude (ELA) of the glacier was 2880 m a.s.l. (Zuo & Oerlemans, 1997). Regional differences in the ELA are primarily related to the precipitation patterns and the aspect of the glaciers (Rott, 1993).

The Pasterze Glacier reached its maximum position of the last 150 years in 1851 (Zuo & Oerlemans, 1997). The terminus of the Pasterze Glacier has retreated during most years of its record and every year since the winter of exceptionally heavy snow in 1965–1966. The total cumulative recession as measured on the ground was ~ 1229 m from 1880 to 2001 (Österreichischer Alpenverein, 1999/2001; Wakonigg, 1991). Previous work showed that between 1984 and 1990, the terminus of the glacier receded at an average speed of ~ 15 m $a^{-1}$ according to measurements made using Landsat Thematic Mapper (TM) data, for a total recession of 90 m (Bayr et al., 1994; Hall, Williams, & Bayr, 1992), while ground measurements showed a total recession of 102 m (17 m $a^{-1}$) over that same period. Retreat and volume loss of the Pasterze Glacier tongue have intensified since 1982 (Wakonigg & Tintor, 1999). Since about 1982, during the period of negative mass balance, the specific net balance of glaciers in the Hohe Tauern has been highly correlated with summer temperatures and not with the amount of winter precipitation (Schöner et al., 2000).


Fig. 1. Location map showing Austria. The circle in southwestern Austria shows the approximate location of the Hohe Tauern.

The Kleines Fleißkees (47°3′ N, 12°57′ E) is a small glacier that is located in the Goldberggroup, east of the Pasterze Glacier. The glacier flows from the Hohe Sonnblick (3105 m), and its terminus movement has been measured annually since 1850. The Kleines Fleißkees receded about 300 m between 1850 and 1870 and, following that, was roughly stable until 1925 (Auer, Böhm, Leymullër, & Schöner, 2002). Since then, the glacier has receded nearly continuously with only one weak advance around 1980. Böhm, Hammer, and Stoble (1983) showed that the ice volume increased between 1969 and 1979 and that the glacier gained 4.4 m in height during this time period. However, between 1979 and 1998, the glacier lost 14 m in height (Auer et al., 2002). The front of the Kleines Fleißkees receded a total of 972 m from 1850 to 2001, or ~ 6.4 $a^{-1}$ on average, according to the ground measurements. Bayr et al. (1994) showed an increase in the exposed ice area of the Kleines Fleißkees from 1984 to 1988, while ground measurements showed a recession of 44 m during that period.

Table 1
Landsat (MSS, TM, or ETM+) and Ikonos data used in this paper

| Sensor | Date | Path/row | Scene ID number |
|---|---|---|---|
| MSS | August 26, 1976 | 206/27 | 8D20602776239 |
| TM | August 3, 1984 | 192/27 | LT5192027008421610 |
| TM | August 9, 1986 | 192/27 | LT5192027008622110 |
| TM | August 6, 1988 | 192/27 | LT4192027008821910 |
| TM | August 4, 1990 | 192/27 | LT5192027009021610 |
| TM | August 1, 1992 | 192/27 | LT4192027009221410 |
| ETM + | July 22, 2000 | 192/27 | LE7192027000020450 |
| Ikonos | September 27, 2000 | N/A | 2000092709463890000011622536 |
| ETM + | August 26, 2001 | 192/27 | LE7192027000123850 |
| Ikonos | October 3, 2001 | N/A | 2000011178400THC |

### 2.1. Satellite data

The Landsat Multispectral Scanner (MSS) was first launched in July 1972 on board the Landsat-1 satellite, providing images at a pixel resolution of approximately 80 m, in four spectral bands in the visible and near-infrared parts of the electromagnetic spectrum. The TM sensor was first carried on the Landsat-3 satellite in 1982. It provided 28.5-m pixel resolution images of the Earth's surface in seven spectral bands, ranging from the visible to the thermal-infrared part of the spectrum. The Enhanced Thematic Mapper Plus (ETM+) (http://landsat.gsfc.nasa.gov/index.htm) was launched on the Landsat-7 satellite in 1999. It has eight discrete bands ranging from 0.45 to 12.5 μm; the spatial resolution ranges from 15 m in the panchromatic band, to 60 m in the thermal-infrared band, and all of the other bands have 30-m resolution. Each Landsat image covers an area 185 km on a side. A detailed comparison of the various band widths and other characteristics of the Landsat sensors may be found at http://landsat.gsfc.nasa.gov/project/Comparison.html.

The Ikonos-1 satellite was launched on September 24, 1999, by Space Imaging. Ikonos collects 4-m resolution multispectral data simultaneously in blue, green, red, and near-infrared bands located at 0.45–0.52, 0.52–0.60, 0.63–0.69, and 0.76–0.90 μm, respectively, and 1-m resolution panchromatic imagery at 0.45–0.90 μm. The Ikonos images cover an area that is nominally 11 km on a side.

Much work has been done to measure glacier changes from space (e.g., see Dowdeswell et al., 1997; Hall et al., 2000; Williams, Hall, & Benson, 1991). Generally, measurements of glacier change are done manually; however, recent work shows that it may be possible to measure many glacier changes using automated techniques (Bishop et al., 2000).

### 2.2. Topographic maps

Excellent topographic maps are available of this area from the late 1800s to the present. The oldest map that we found, dated 1893, shows the greatest areal extent of the Pasterze tongue (Spezialkarte von Österreich-Ungarn, 1893). Another map showing the 1928 "Gletscherstand" (glacier position) was also obtained (Deutscher und Österreichischer Alpenverein, 1928) and shows a somewhat smaller terminus than that observed on the 1893 map. Austrian Alpine Club maps were employed to measure the areal extent of the terminus (Österreichischer Alpenverein, 1982/1992) and to compare the Gletscherstand with the terminus position derived from satellite imagery. The Austrian Alpine Club maps are updated regularly and sometimes only the Gletscherstand is updated. The date of the Pasterze Gletscherstand is given on the maps, and this date is different from the publication date of the maps. The 1982 map shows the 1965 Gletscherstand, and the 1992 map shows the 1985 Gletscherstand. The accu-

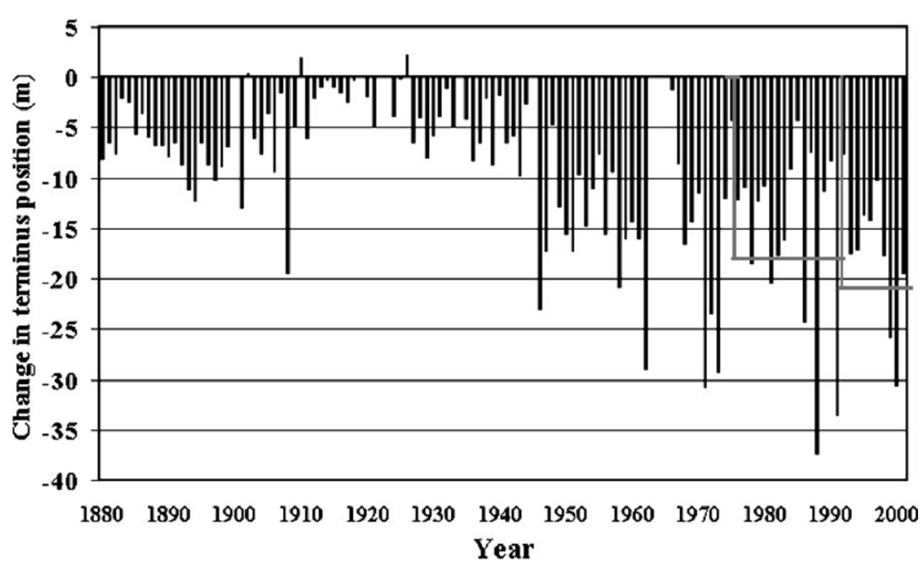


Fig. 2. Recession of the Pasterze Glacier tongue as measured on the ground from 1880 to 2001 (Österreichischer Alpenverein, 1982/1992; Wakonigg, 1991). The red boxes show the average recession (in m $a^{-1}$) measured from Landsat data.

racy of the Gletscherstand as shown on the maps is not reported.

In addition, Leonard and Fountain (in press) discuss two methods to estimate the ELA of glaciers from topographic maps. They conclude that topographic maps of glacier surfaces can be used to infer the position of the ELA, and that their methods are useful for estimating past ELAs from historic topographic maps.

## 3. Methodology

For this study, topographic maps were used to measure the extent of the Pasterze Glacier tongue over approximately the last century, and to compare earlier terminus positions (from maps) with more recent terminus positions derived from satellite imagery. Also Landsat scenes from 1976, 1984, 1986, 1988, 1990, 1992, 2000, and 2001 and Ikonos scenes from 2000 and 2001 were studied (Table 1).

All of the Landsat images listed in Table 1 were registered digitally to the 1984 Landsat TM scene (which is used as the "base"), having a pixel resolution of 28.5 m, to enable measurement of changes of the terminus position of the glacier between years. To register scenes or maps, about 100 tie points, points in common between the 1984 and the other TM or ETM+ images were determined. A second-order polynomial was used to warp each image or map to the 1984 TM base image, with a registration accuracy of 0.5 pixel, or 14 m. The registration error, when registering the 1976 MSS image (80-m resolution), to the TM or ETM+ images was 0.8 pixel, or 23 m. The September 27, 2000 and the October 3, 2001 Ikonos images are georeferenced.

Once registered to a common base, changes in the terminus position of the Pasterze Glacier can be measured digitally with an accuracy of ± 40 m when using TM or ETM+ only, and ± 113 m when registering the 1976 MSS scene to the 1984 TM scene if the registration of the images is perfect. This is determined from the following formula (Williams, Hall, Sigurdsson, & Chien, 1997):

$$\text{Uncertainty} = \sqrt{28.5^2 + 28.5^2} \tag{1}$$

for the 28.5-m resolution TM or ETM+ data. However, the registration error must also be included, so the accuracy is actually ± 54 m, and ± 136 m for the case where an MSS image is registered to a TM or ETM+ image. This registration technique was also used to measure the glacier terminus position change from 1893 to 2001; however, error bars cannot be assigned because the accuracy of the glacier terminus position on the 1893 map is unknown.

To improve the contrast between the glacier ice and surrounding areas on the 1976 MSS scene, a false color composite image was constructed using MSS bands 4 (0.8–0.11 μm), 2 (0.63–0.76 μm), and 1 (0.45–0.52 μm). Good contrast between the Pasterze Glacier tongue and the surrounding terrain was achieved using TM or ETM+ band 5 (1.55–1.75 μm), which is a short-wave infrared band, and thus band 5 imagery was used to measure the position of the glacier tongue using the TM and ETM+ images. Because a

Table 2
Errors determined in this study for measuring glacier termini when registering maps or satellite images

| Map or image | Error (m) |
|---|---|
| Map to satellite | Unknown error |
| MSS to TM[a] | ± 136[b] |
| TM[a] to TM[a] | ± 54[b] |
| TM[a] to ETM+ | ± 54[b] |
| ETM+ to ETM+ | ± 40 |
| 4-m Ikonos to 4-m Ikonos | ± 5.7 |
| 1-m Ikonos to 1-m Ikonos | ± 1.4 |

[a] Older TM data are not geocoded.
[b] Includes Registration error.

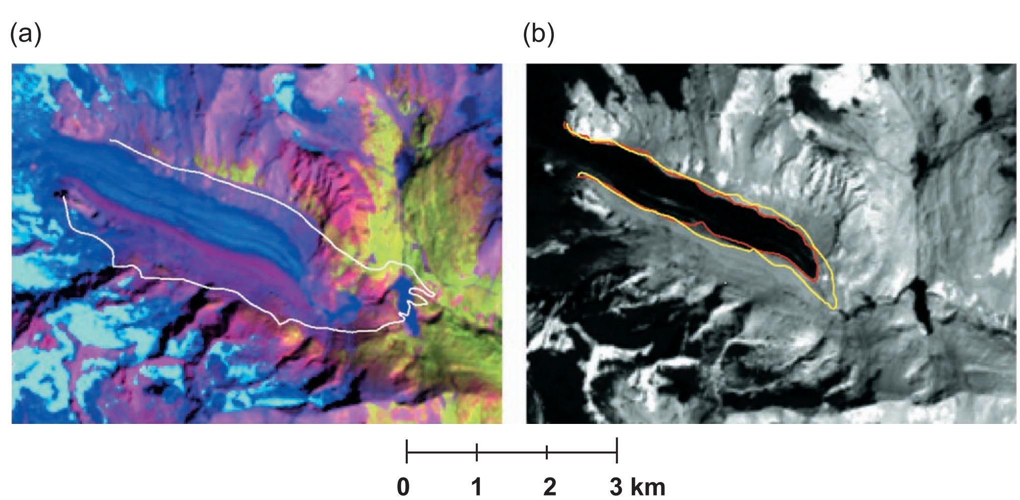


Fig. 3. (a) Representation of the 1893 position of the Pasterze Glacier tongue from the map is shown in white (Spezialkarte von Österreich-Ungarn, 1893) relative to the 2001 position on the August 26, 2001, Landsat ETM+ image, false color composite. (b) ETM+ band 5 (1.55–1.75 μm) image from August 26, 2001, showing changes in the position of the exposed ice part of the Pasterze Glacier tongue from 1976 (yellow line) to 2001 (red line).

Table 3
Average recession (m) of Pasterze Glacier terminus using ground data (1880–2001) and satellite data (1976–2001)

| Years of measurements | Total recession (m) from satellite measurements and average rate of recession (m $a^{-1}$) in parenthesis | Total recession (m) from ground measurements and average rate of recession (m $a^{-1}$) in parenthesis[a] |
|---|---|---|
| 1880–1976 | N/A | – 800.7 (8.4) |
| 1976–1984 | – 145.3 ± 136 (18.1) | – 127.7 (16.0) |
| 1984–1992 | – 142.5 ± 54 (17.8) | – 134.0 (19.1) |
| 1992–2001 | – 191.2 ± 54 (21.2) | – 166.1 (20.8) |

[a] Uncertainty not reported, but expected to be very small (~ ± 1 m).

short-wave infrared band was not available on the MSS sensor, the false color composite was used.

To establish the accuracy of determining the Pasterze Glacier terminus position as indicated on the topographic map, the difference in the positions was determined from a 1984 TM image and the topographic map with a 1985 Gletscherstand.

Changes in the areal extent and surficial conditions of the Kleines Fleißkees were measured with an accuracy of $\pm 0.0023$ km$^2$ using TM and ETM+ images, and the following formula:

$$a = A^*(2d/x) \quad (2)$$

where $a$ is the desired uncertainty in area; $A = x^2$, where $x$ = linear side dimension (28.5 m for TM or ETM+ data); and $d$ is the uncertainty in the linear dimension (from Eq. (1)).

The temperature and precipitation data from the Sonnblick Observatory (SBO) (3105 m), located about 15 km east of the tongue of the Pasterze on the top of Hohe Sonnblick, are also shown. The proximity of the Pasterze Glacier to Hohe Sonnblick offers the opportunity to compare the satellite-derived glacier measurements with a tem-

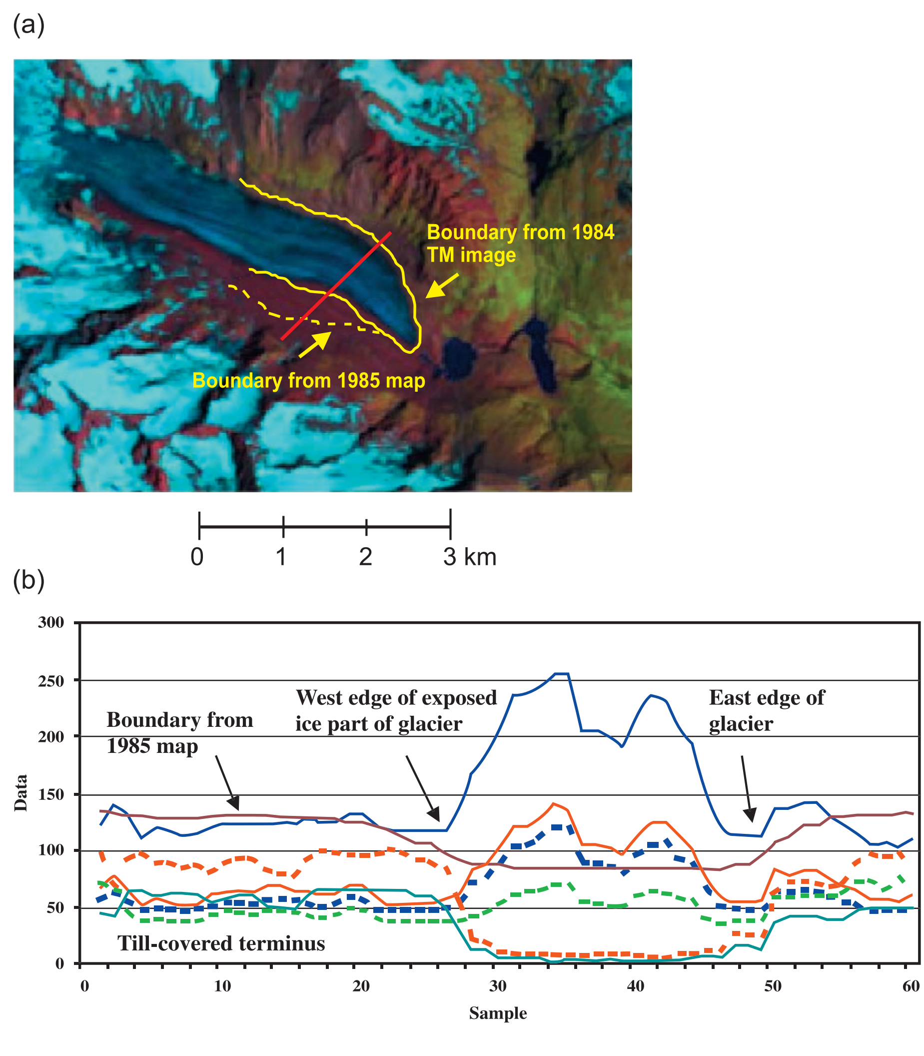


Fig. 4. (a) Landsat TM color composite image, August 3, 1984, showing the satellite-derived position of the Pasterze Glacier tongue (solid yellow line), and the extent of the tongue from the map with a 1985 Gletscherstand (dotted yellow line); the red line represents the transect (NE to SW) shown in (b). (b) Digital counts from the Landsat TM bands across the Pasterze Glacier tongue as measured from the transect (solid red line) in (a).

perature and precipitation record from meteorological data acquired at SBO since 1887.

The record of ground measurements of the Pasterze Glacier (Fig. 2) is missing for a span of 7 years. To fill in the missing years, the year before and the year after the missing years were averaged. That average value was inserted in the missing year(s) as an estimate of the recession for that year. There were no missing measurements in the >150-year record of terminus measurements of the Kleines Fleißkees.

## 4. Results of the Pasterze Glacier study

### *4.1. Glacier tongue changes and measurement uncertainties*

The extent of the Pasterze Glacier tongue in 1893 and 2001 is depicted in Fig. 3a, and in 1976 and 2001 in Fig. 3b. Fig. 3a is a color composite (bands 5, 4, and 2) of the August 26, 2001 ETM+ image showing the glacier tongue. The recession from 1893 to 2001, measured using map and satellite data, is difficult to compare with the ground measurements because the recession varies depending at which point on the terminus is selected, and the tongue did not retreat uniformly across its width. Nevertheless, we determine a recession of 1300–1800 m (error is unknown because the accuracy of the Gletscherstand on the maps is unknown), depending on what point is selected on the terminus. Ground measurements (the summation of changes, in meters, in individual years) show a recession of $\sim$ 1150 m from 1893 to 2001 (Österreichischer Alpenverein, 1999/2001; Wakonigg, 1991). This represents a difference of 150–650 m, which is quite large due, in part, to the extreme difficulty in registering the 1893 map to the 1984 Landsat image.

The 1928 position of the glacier tongue was also studied (Deutscher und Österreichischer Alpenverein, 1928) and the tongue was found to be narrower, on the eastern side of the glacier, and shorter than it was in 1893. According to the ground measurements, the glacier terminus receded 161 m from 1893 to 1928.

Table 2 shows the errors calculated for digitally comparing the map and satellite data. The errors include the uncertainty in measuring changes between scenes as well as the registration error (when applicable), which is calculated from the image processing program.

Recession of the Pasterze Glacier terminus and narrowing of the exposed parts of its tongue were measured using Landsat data acquired in the summers of 1976–2001 (Fig. 3b). The total recession, as measured from 1976 to 2001 at the farthest reach of the exposed ice part of the tongue, is 479.0 $\pm$ 136 m (or an average rate of $\sim$ 19.1 m $a^{-1}$), while ground measurements show a recession of 428.5 m ($\sim$ 17.1 m $a^{-1}$). Table 3 shows the position of the glacier terminus change from topographic maps, satellite data, as well as from the ground measurements.

When the 1992 topographic map (with a 1985 Gletscherstand for the Pasterze Glacier) was registered to the 1984 Landsat scene, visual inspection showed that the terminus positions matched within about two TM pixels, or $\pm$ 57 m. This is comparable to the uncertainty that was calculated previously for TM or ETM+ images ($\pm$ 54 m) and thus establishes the approximate accuracy of measuring glacier changes using a high-quality recent topographic map and a satellite image.

Even on the ground, it can be difficult to tell the exact position of the terminus of the Pasterze Glacier because of obscuring surface debris. Field measurements in August 2001 indicate that the thickness of the morainal material covering part of the Pasterze tongue varies from a few centimeters to about a meter. Hanging glaciers above the western side of the Pasterze tongue contribute morainal material to the Pasterze tongue, thus accounting for a large amount of debris on that side of the glacier tongue. As the glacier recedes, the debris collects on the surface of the ice. Inspection of the digital numbers (DNs) from the Landsat data (using all seven bands) shows that data from the TM

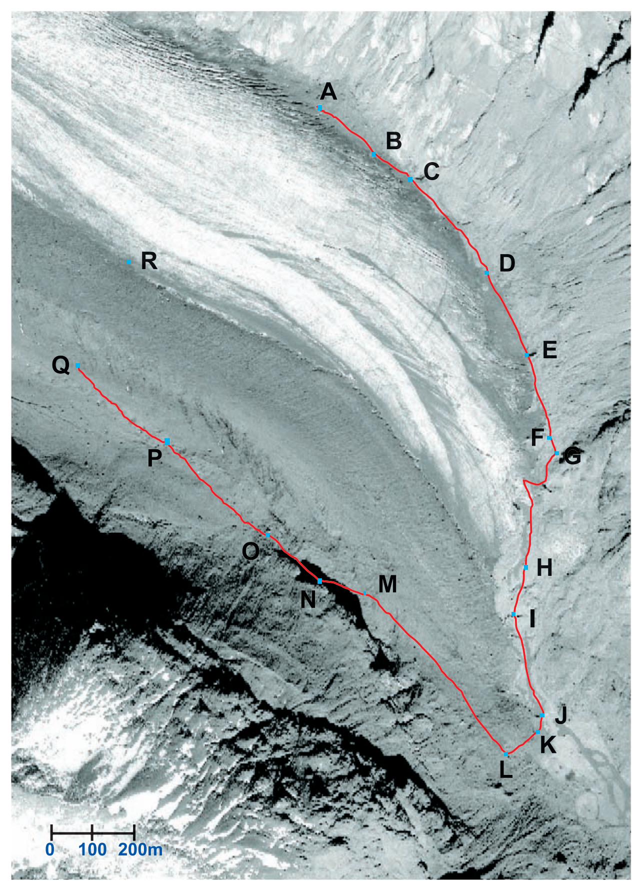


Fig. 5. The base image is the October 3, 2001 1-m resolution Ikonos image (panchromatic band; 0.45–0.9 μm). Global positioning system measurements from August 23, 2001 are shown as blue points. The red line that connects the points delimits the glacier terminus. Point “R” (in the center of the glacier) represents the location of the supraglacial stream that divides the till-covered from the exposed ice parts of the Pasterze Glacier terminus.

sensor cannot distinguish glacier ice below surface debris of the glacier tongue. In Fig. 4a, the 1984 image is shown with a solid yellow line outlining the visible part of the tongue. The dotted line in the western part of the tongue shows the actual position of the tongue as the map (Österreichischer Alpenverein, 1982/1992). In Fig. 4b, a transect across the image at the red line (northeast to southwest) in Fig. 4a shows that in the debris-covered part of the terminus (the southwestern part of the terminus), the DNs cannot be used to distinguish the ice below. The debris-covered ice constituted approximately 26% of the total areal extent of the glacier tongue in 1984, and approximately 25% in 2001.

The August 2001 boundary of the lower part of the Pasterze Glacier tongue was verified using global positioning system (GPS) measurements made at the terminus of the Pasterze on August 23, 2001. The GPS measurements were obtained while hiking along the perimeter of the lower part and the terminus of the glacier. In the case of the debris-covered part of the glacier, it was necessary first to verify the exact location of the glacier by noting the presence or absence of ice underneath the surficial debris. The GPS points are shown on the October 3, 2001, 1-m resolution Ikonos panchromatic image (Fig. 5). The accuracy for each GPS point is shown in Table 4. The lines connecting the points represent our estimate of the glacier boundary based on field work by one of the authors (K.J.B.). Point "R" represents a point at which the supraglacial stream is located. The supraglacial stream is the approximate boundary between the till-covered and till-free parts of the tongue. Point "L" represents the farthest extent of the glacier.

Comparison of the 4-m resolution false color Ikonos images from September 27, 2000 and October 3, 2001 reveals a decrease in area of the terminus of $22{,}096 \pm 46$ $m^2$ (Fig. 6a and b). This quantifies observations by one of the authors (K.J.B.) whereby a noticeable recession of the terminus was observed on the ground from the summer of 2000 to the summer of 2001.

Table 4
Accuracy of GPS points acquired on August 23, 2001 on the Pasterze Glacier tongue

| Point | Accuracy (m) |
|---|---|
| A | 10 |
| B | 11 |
| C | 7 |
| D | 6 |
| E | 5 |
| F | N/A |
| G | 6 |
| H | 8 |
| I | 8 |
| J | 8 |
| K | 9 |
| L | 11 |
| M | 21 |
| N | 13 |
| O | 5 |
| P | 11 |
| Q | 3 |
| R | 9 |

Accuracy is based on the number of satellites available.

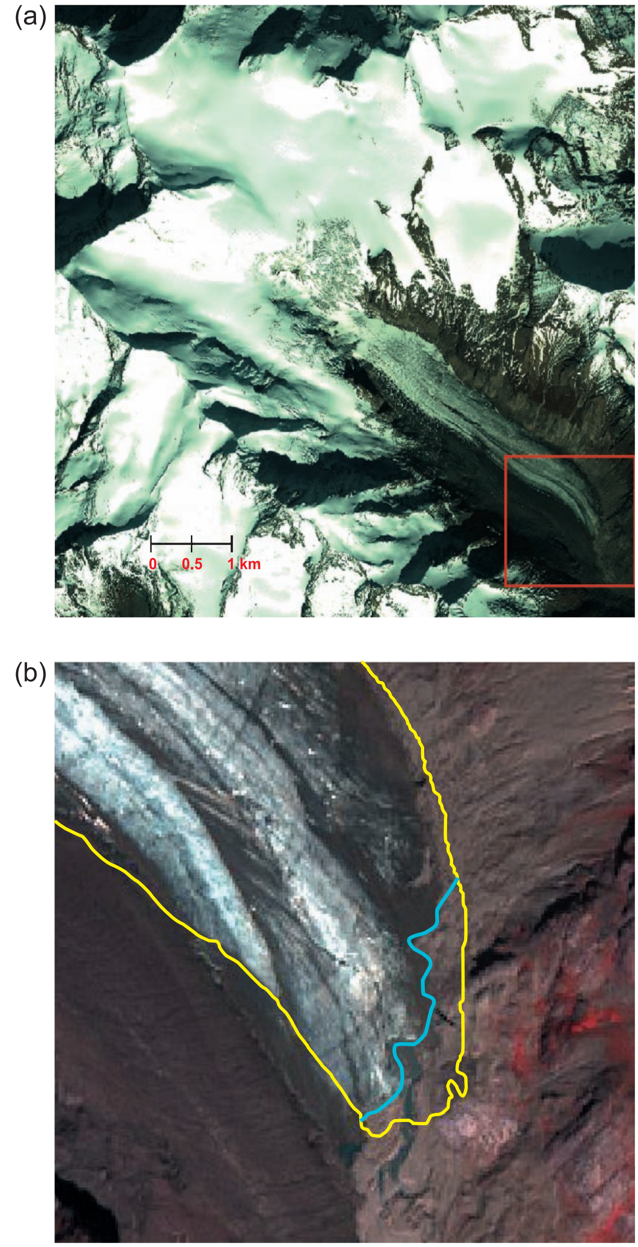


Fig. 6. (a) Four-meter resolution Ikonos false color image from October 3, 2001 showing the tongue of the Pasterze Glacier; the red box shows the area covered in (b). (b) Zoomed Ikonos 4-m resolution image of the Pasterze Glacier terminus from October 3, 2001. The yellow line is a trace of the position of the exposed ice area of the terminus as measured from the September 27, 2000 Ikonos image; the blue line shows the extent of the exposed ice area on the 2001 image.

## 5. Results of the Kleines Fleißkees study

Full-resolution, false-color (bands 5, 4, and 2) TM (1984 and 1992) and ETM+ (2001) images of the Kleines

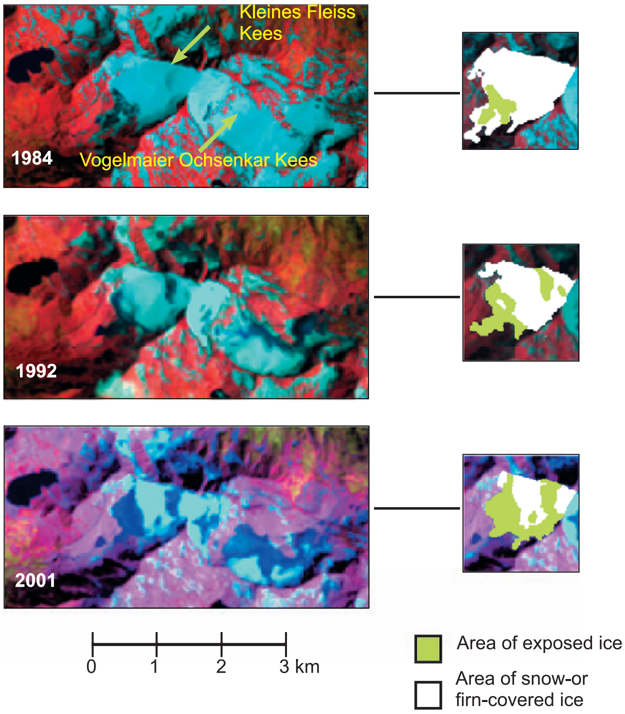


Fig. 7. Landsat images at full resolution (28.5 m) of the Kleines Fleißkees and Vogelmaier Ochsenkar Kees from 1984, 1992, and 2001. The classified subimages of the Kleines Fleißkees superimposed on a false color composite image (TM or ETM+ bands 5, 4, and 2) are adjacent to the corresponding Landsat image.

Table 5
Areal extent and area of exposed ice of the Kleines Fleißkees, as measured using Landsat data

| Date | Total area ($km^2$) | Exposed ice area ($km^2$) | Percent of total |
|---|---|---|---|
| August 3, 1984 | 1.45 | 0.18 | 12.4 |
| August 1, 1992 | 1.17 | 0.42 | 36.0 |
| August 26, 2001 | 1.02 | 0.62 | 60.8 |

Fleißkees and the adjacent Vogelmaier Ochsenkar Kees glaciers are shown in Fig. 7. The extent of the Kleines Fleißkees was measured in each of the 3 years. We also measured the approximate boundaries of the ablation and accumulation areas (Benson, 1962). If the exposed ice area is the same as the ice facies (Benson, 1962), then an accumulation area ratio (AAR) (Paterson, 1994) of 0.39 can be calculated for 2001 since the 2001 image was acquired near the end of the melt season. However, it is possible that a new summer snow cover, if only temporary, was present; thus, the exposed ice area may not coincide with the ice facies. If fresh snow were present, the ice facies would be smaller and the AAR would appear to be larger. An AAR of 0.39 indicates a glacier with a negative mass balance.

Ground measurements of the terminus retreat of the Kleines Fleißkees are included to show that it has been retreating dramatically especially in recent years. However, the size of the Kleines Fleißkees is such that it is difficult to measure the actual recession of the terminus using the 30-m resolution Landsat ETM+ data. Therefore, changes in areal extent have been measured as discussed below.

The Kleines Fleißkees experienced major shrinkage between 1984 and 2001 as shown in Fig. 8 and Table 5. Satellite measurements from 1984 to 2001 show that the glacier lost ∼ 30% of its area from 1984 to 2001; the area of exposed ice increased by $0.44 \pm 0.0023$ $km^2$ over this period. Since the 1984 and 1992 images were acquired in early August, and the 2001 image was acquired at the end of August, the increase between years in the exposed ice

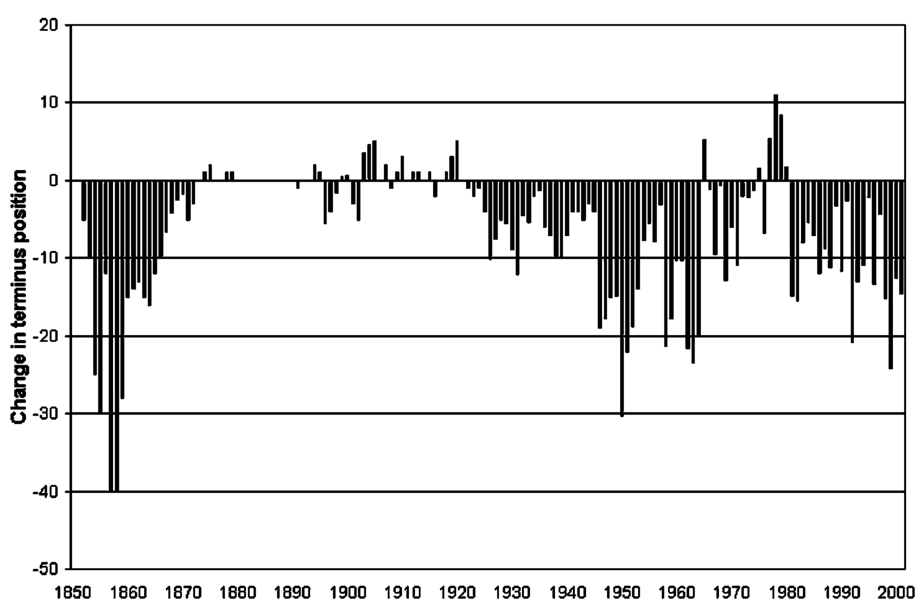


Fig. 8. Recession of the Kleines Fleißkees as measured on the ground from 1850 to 2001 (Auer et al., 2002).

area is probably not very meaningful. Bare ice comprised nearly 61% of the total area of the glacier in late August 2001.

## 6. Possible causes of glacier recession

Wakonigg and Tintor (1999) showed that the recession of the Pasterze terminus has intensified since 1982. The average rate of recession for the entire period of record (1880–2001) is 10.2 m $a^{-1}$ according to the ground data. Between 1880 and 1981, the average rate of recession is 8.8 m $a^{-1}$, while it is 18.1 m $a^{-1}$ from 1982 to 2001.

Although changes of the front position of a glacier result from both mass balance variability (from weather trends) and individual flow dynamics of a glacier, it is out of the scope of this paper to discuss the flow dynamics of Pasterze and Kleines Fleißkees.

Changes of specific net balance of a glacier can be explained by changes of summer air temperature and

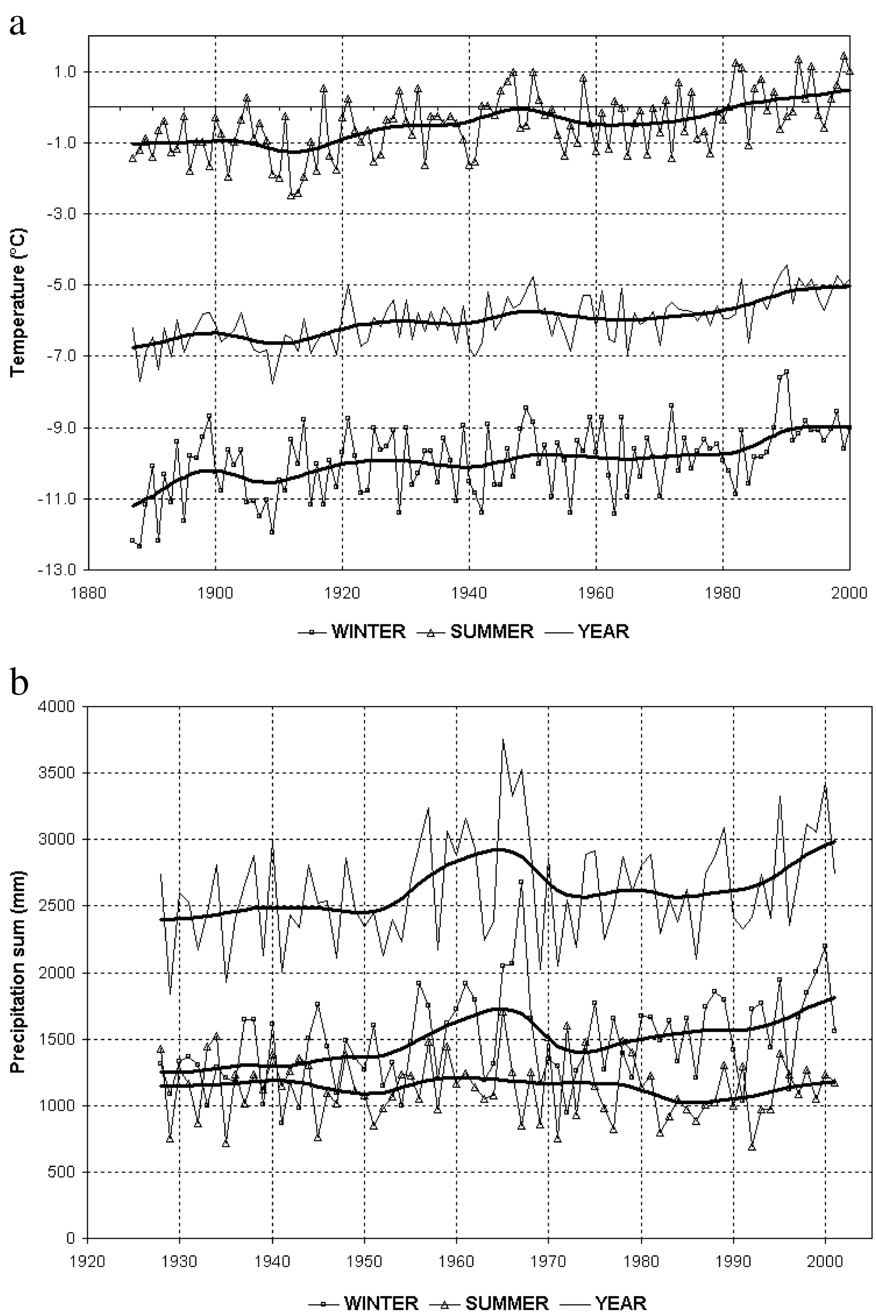


Fig. 9. (a) Average annual and average spring/summer (May through September) temperature (in °C) from the Sonnblick Observatory, Austria, 1887–2000. (b). Annual total and spring/summer total (May through September) precipitation (in cm) from the Sonnblick Observatory, Austria, 1927–2000 (Schöner et al., 2000).

amount of winter precipitation (falling as snow). There is a particularly high correlation between summer air temperature and short-wave radiation balance. This is especially true for high elevation climate stations such as SBO (Auer, Böhm, & Schöner, 2001; Schöner et al., 2000). In Fig. 9, a time series of annually averaged summer air temperature (May to September, since 1887) and winter precipitation (October to April, since 1927) is shown along with the 30-year low-pass filtered values. There is a decrease in summer temperature beginning around 1911 or 1912 (Fig. 9a), and this is most likely responsible for a general glacier advance in the Austrian Alps around this time. A glacier recession in the Austrian Alps after 1920 was due to increasing summer temperature with a maximum around 1950. The glacier maximum around 1980 was caused by reduced summer temperatures, and increased winter precipitation (Fig. 9b) in the 1960s and 1970s.

For the Pasterze Glacier, the more positive mass balances in the early 1880s and between ~ 1910 and 1920 resulted only in a roughly stable length of the tongue around 1920, and in a slightly reduced retreat in the 1970s. This may be because the response time, on the order of 50–70 years (Johannesson, Raymond, & Weddington, 1989), is long enough that the years with positive mass balance did not result in an advance before the negative mass balances of later years occurred. Changes in the smaller Kleines Fleißkees more closely track the climate trends. Around the 1880s and early 1900s and around 1980, the Kleines Fleißkees showed advances. A detailed discussion of climate variability and glacier recession in the Austrian eastern Alps can be found in Schöner et al. (2000).

Climate data from SBO show that the average summer temperature increased by 1.7 °C from 1910 to 2001. This general warming resulted from two major warming periods: the first between 1910 and about 1950, and the second between about 1970 and 2001. There was a period of general cooling between about 1950 and 1970. Long-term precipitation data from SBO show a large increase of winter precipitation in the 1960s, which helps to explain periods of general glacier advance in 1960s and 1970s. A decrease in winter precipitation along with increased summer temperatures helps to explain glacier recession in the 1980s. Even a significant increase in precipitation cannot compensate for increased melting if the summer temperatures are high (Oerlemans & Fortuin, 1992).

In addition to the regional climate variability, glacier mass balance is also influenced by local climate effects (e.g., the katabatic winds for large valley glaciers). Van den Broeke (1997) showed that strong and very persistent gravity (katabatic) winds on the Pasterze Glacier tongue enhance the melting of the ice and snow on the tongue.

## 7. Discussion and conclusions

Largely due to warm summer temperatures, both the Pasterze and the Kleines Fleißkees have receded dramatically especially since the early 1980s. We show that the recession, as measured by Landsat data, is comparable to the recession as measured on the ground (within the uncertainty of the satellite measurement technique) (Table 6).

It is sometimes impossible to measure accurately the position of a glacier terminus from space. This was demonstrated in Williams et al. (1997) in a study of glacier changes on Vatnajökull, Iceland, using Landsat data. When a glacier is in recession, debris may collect on the surface of part or all of the glacier tongue and the glacier will have a spectral reflectance similar to the surrounding moraine. This can make the exact terminus difficult to locate, especially from space. Advancing glaciers, and other receding glaciers such as tidewater glaciers with clean termini, are generally easier to measure from space (Hall, Benson, & Field, 1995; Sturm, Hall, Benson, & Field, 1991). However, even on receding glaciers with copious amounts of surficial morainal material such as that which occurs on the Pasterze Glacier, good results can be obtained by monitoring glacier changes from space as shown in this paper. On the ground, the terminus position can usually be determined by digging into the top layers of the debris, but this is a very labor-intensive activity. If ice is found, then that may represent the position

Table 6
Comparison of ground and Landsat-derived measurements from Iceland (Williams et al., 1997) and the Pasterze Glacier, Austria

| Glacier | Years of measurement | Landsat measurement (m) | Ground measurement (m) | Difference between Landsat and ground measurement (m) |
|---|---|---|---|---|
| Morsárjökull, Iceland | 1973–1987 | + 143 ± 136 | + 143 ± 1 | 0 |
| Pasterze, Austria | 1976–2001 | − 479 ± 136 | − 428 ± 1 | 51[a] |
| | 1984–1992 | − 143 ± 54 | − 134 ± 1 | 9[a] |
| | 1992–2001 | − 191 ± 54 | − 166 ± 1 | 25[a] |
| Sidujökull, Iceland | 1973–1987 | − 513 ± 136 | − 643 ± 1 | 130 |
| Skeidarárjökull (E), Iceland | 1987–1992 | + 223 ± 54 | + 276 ± 1 | 53 |
| Skeidarárjökull (W), Iceland | 1973–1987 | + 257 ± 136 | + 244 ± 1 | 13[a] |
| Tungnaárjökull, Iceland | 1973–1987 | − 1140 ± 136 | − 1130 ± 1 | 10[a] |
| | 1973–1992 | − 1413 ± 136 | − 1380 ± 1 | 33[a] |

[a] Satellite measurement is higher.

of the terminus, although stagnant ice, unconnected to the glacier tongue, may further confuse the determination of the terminus.

The difference between the total recession of the Pasterze Glacier tongue estimated from the 1893 map registered to the 2001 Landsat-derived map, and the ground measurements varies from 150 to 650 m. The difference is likely due to the uncertainty of the accuracy of the Gletscherstand on the 1893 map, and the uncertainty associated with the registration of the map and ETM+ image. Also, different parts of the terminus showed different amounts of recession, and the amount of recession measured was dependent upon where on the terminus the measurement was made.

From 1976 to 2001, ground measurements show that the Pasterze Glacier tongue receded ~ 428 m (or 17.1 m $a^{-1}$ on average), while measurements using Landsat data show a recession of $479 \pm 136$ m (or 19.1 m $a^{-1}$ on average). Deterioration of the Pasterze Glacier tongue is evident even when only about 1 year intervened between Ikonos images (from September 27, 2000 to October 3, 2001) where a decrease in area of $22,096 \pm 46$ $m^2$ was measured using 4-m resolution Ikonos images.

The smaller Kleines Fleißkees lost 30% of its area between 1984 and 2001, according to satellite measurements, and had an AAR of ~ 0.39 in 2001, which is indicative of a glacier with a negative mass balance.

When a high-quality topographic map and satellite image were registered, and the glacier terminus position was compared for nearly the same time period—1985 Gletscherstand and 1984 satellite image—the agreement of the terminus position was within two TM pixels (57 m), which is comparable to the $\pm$ 54 m uncertainty calculated for non-georeferenced TM images.

The Landsat database, beginning in 1972, enables decadal scale glacier changes to be measured with increasing detail, and is an important resource for measuring glacier changes and correlating those changes with regional climate changes in most glacierized areas on the Earth. Sensors like the Ikonos, with up to 1-m resolution, provide even better resolution for studying detailed changes between years, and are especially good for detailed mapping of the glacier tongue. High-quality aerial photographs also represent valuable information. However, accurate registration and comparison of aerial photographs and satellite imagery are often extremely difficult.

We have shown that uncertainties can be considerable when comparing satellite data with topographic maps, especially old maps, but that the uncertainties are much lower when recent, high-quality topographic maps are compared with satellite imagery. As extensive use is made of the three-decade long Landsat database, it is important to know the measurement errors when measuring glacier changes. These errors are getting increasingly smaller as the resolution and geocoding of the satellite images improve over time.

## Acknowledgements

The authors would like to thank Dr. Heinz Slupetzky (University of Salzburg), Dr. Helmut Rott (University of Innsbruck, Austria), and Dr. Gerhard Karl Lieb (University of Graz, Austria) for providing us with information and data on the Pasterze Glacier. The funding for this work was provided by NASA.

## References

Auer, I., Böhm, R., & Schöner, W. (2001). Austrian long-term climate 1767–2000—multiple instrumental climate time series from central Europe. *Österreichische Beiträge zu Meteorologie und Geophysik*, *25* (147 pp.).

Auer, I., Böhm, R., Leymüller, M., & Schöner, W. (2002). Das Klima des Sonnblicks-Klimaatlas und Klimatographie der GAW-Station Sonnblick einschließlich derumgebenden Gebirgsregion. *Österreichische Beiträge zu Meteorologie und Geophysik Heft*, *28* (304 pp.) .

Bayr, K. J., Hall, D. K., & Kovalick, W. M. (1994). Observations on glaciers in the eastern Austrian Alps using satellite data. *International Journal of Remote Sensing*, *15*(9), 1733–1752.

Benson, C. S. (1962). *Stratigraphic studies in the snow and firn of the Greenland ice sheet*. Research Report 70. Snow, Ice and Permafrost Research Establishment (now U.S. Army Cold Regions Research and Engineering Laboratory). Reprinted and updated in 1996, 93 pp. + appendices.

Bishop, M. P., Kargel, J. S., Kieffer, H. H., MacKinnon, D. J., Raup, B. H., & Shroder Jr., J. F. (2000). Remote sensing science and technology for studying glacier processes in high Asia. *Annals of Glaciology*, *31*, 164–170.

Böhm, R. (1986). *Der Sonnblick*. Vienna: Öesterreichischer Bundesverlag, 222 pp.

Böhm, R., Hammer, N., & Stoble, J. (1983). Analyse der Veränderungen von drei benachbargen alpinen Gletschern in der Goldberggruppe der Hohen Tauern seit 1930. *Mitteilungen der Öesterreichischen Geographisschen Gesellschaft*, *125*, 116–151.

Deutscher und Österreichischer Alpenverein (1928). *Karte der Glocknergruppe*, 1:25,000.

Dowdeswell, J. A., Hagen, J. O., Björnsson, H., Glazovsky, A. F., Harrison, W. D., Holmlund, P., Jania, J., Koerner, R. M., Lefauconnier, B., Ommanney, C. S. L., & Thomas, R. H. (1997). The mass balance of circum-arctic glaciers and recent climate change. *Quaternary Research*, *48, 1–14.*

Dyurgerov, M. (2002). *Glacier mass balance and regime: Data of measurements and analysis*. Occasional Paper No. 55. Boulder, CO: Institute of Arctic and Alpine Research, University of Colorado, 268 pp.

Haeberli, W., Cihlar, J., & Barry, R. G. (2000). Glacier monitoring within the global climate observing system. *Annals of Glaciology*, *31*, 241–246.

Haeberli, W., & Hölzle, M. (1995). Application of inventory data for estimating characteristics of and regional climate-change effects on mountain glaciers: A pilot study with the European Alps. *Annals of Glaciology*, *21*, 206–212.

Hall, D. K., Benson, C. S., & Field, W. O. (1995). Changes of glaciers in Glacier Bay, Alaska, using ground and satellite measurements. *Physical Geography*, *16*(1), 27–41.

Hall, D. K., Williams, R. S. Jr., Barton, J. S., Sigurdsson, O., Smith, L. C., & Garvin, J. B. (2000). Evaluation of remote-sensing techniques to measure decadal-scale changes of Hofsjökull ice cap, Iceland. *Journal of Glaciology*, *46*(154), 375–388.

Hall, D. K., Williams, R. S. Jr., & Bayr, K. J. (1992). Glacier recession in Iceland and Austria as observed from space. *Eos, 73*(12), 129, 135, 141.

Hölzle, M., Dischl, M., & Frauenfelder, R. (2000). Weltweite Gletscherbeobachtung als Indikator der globalen Klimaänderung. *Vierteljahresschrift der Naturforschenden Gesellschaft in Zürich*, *145*(1), 5–12.

Johannesson, T., Raymond, C., & Waddington, E. (1989). Time scale for adjustment of glaciers to changes in mass balance. *Journal of Glaciology*, *35*(121), 355–369.

Leonard, K. C., & Fountain, A. G. (in press). Map-based methods for estimating glacier equilibrium line altitudes. *Journal of Glaciology.*

Nesje, A., & Dahl, S. V. (2000). *Glaciers and environmental change, key issues in environmental change*. UK: Arnold, 203 pp.

Oerlemans, J., & Fortuin, J. P. F. (1992). Sensitivity of glaciers and small ice caps to greenhouse warming. *Science*, *258*, 115–117.

Österreichischer Alpenverein (1982/1992). *Alpenvereinskarte Grossglocknergruppe*, 1:25,000, No. 40.

Österreichischer Alpenverein (1999/2001). http://www.alpenverein.at/gletscherbericht.htm.

Paterson, W. S. B. (1994). *The physics of glaciers* (3rd ed.). Pergamon, 480 pp.

Rott, H. (1993). The glaciers of Europe—glaciers of the Alps. The Austrian Alps. In: R. S. Williams Jr., & J. G. Ferrigno (Eds.), *U.S. Geological Survey Professional Paper, vol. 1386-E* (pp. E6–E13).

Schöner, W., Auer, I., & Böhm, R. (2000). Climate variability and glacier reaction in the Austrian eastern Alps. *Annals of Glaciology*, *31*, 31–38.

Spezialkarte von Österreich-Ungarn (1893). *Grosz-Glockner*, Zone 17, Col. VII, 1:75,000.

Sturm, M., Hall, D. K., Benson, C. S., & Field, W. O. (1991). Non-climatic control of glacier terminus fluctuations in the Wrangell and Chugach Mountains, Alaska, USA. *Journal of Glaciology*, *37*, 347–356.

Van den Broeke, M. R. (1997). Structure and diurnal variation of the atmospheric boundary layer over a mid-latitude glacier in summer. *Boundary Layer Meteorology*, *83*, 183–205.

Wakonigg, H. (1991). Die Nachmessungen an der Pasterze von 1879 bis 1990. *Arbeider fra Geografisk Institutt (Graz)*, *30*, 271–307.

Wakonigg, H., & Tintor, W. (1999). Zum Massenumsatz der Pasterzenzunge zwischen 1979 und 1994. *Wissenschaftliche Mitteilungen aus dem Nationalpark Hohe Tauern, Band*, *5*, 193–203.

Williams, R. S. Jr., & Ferrigno, J. G. (1993). Satellite image atlas of glaciers of the world—Europe. *U.S. Geological Survey Professional Paper*, *1386-E* (164 pp.).

Williams, R. S. Jr., Hall, D. K., & Benson, C. S. (1991). Analysis of glacier facies using satellite techniques. *Journal of Glaciology*, *37*(125), 120–128.

Williams, R. S. Jr., Hall, D. K., Sigurdsson, O., & Chien, J. Y. L. (1997). Comparison of satellite-derived with ground-based measurements of the fluctuations of the margins of Vatnajökull, Iceland, 1973–92. *Annals of Glaciology*, *24*, 72–80.

Zuo, Z., & Oerlemans, J. (1997). Numerical modelling of the historic front variation and the future behaviour of the Pasterze Glacier, Austria. *Annals of Glaciology*, *24*, 234–241.